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Mapping Global Research on Agrochemicals and Sustainability: A Bibliometric Analysis of Environmental and Economic Perspectives

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Abstract

The transition toward sustainable agriculture has intensified global attention on the environmental and economic implications of agrochemical use. Agrochemicals remain vital for food security, yet their misuse contributes to soil degradation, pollution, and greenhouse gas emissions. This study employs a bibliometric approach to examine global research trends, collaboration patterns, and thematic developments linking agrochemicals with environmental sustainability and the green economy. Data were retrieved from the Scopus database covering the period 1976–2025 and analyzed using performance indicators, co-authorship, co-citation, and keyword co-occurrence mapping. The results reveal a continuous increase in publications and citations, particularly after 2018, reflecting the growing relevance of sustainable agricultural practices. Europe and North America dominate scientific output and influence, while developing regions show emerging but limited participation. Thematic analysis indicates a paradigm shift from productivity-driven studies to sustainability-oriented research emphasizing biochar, nutrient recycling, and circular agriculture. Reference co-citation patterns further highlight the integration of environmental policy, agronomic innovation, and economic frameworks.These findings provide a holistic overview of how scientific communities have evolved to address the dual challenge of agricultural productivity and environmental protection. The study contributes to future research and policy formulation by identifying emerging directions for sustainable agrochemical management and reinforcing the need for equitable global collaboration in the transition toward a low-carbon agricultural economy.

Keywords: Bibliometric mapping, Circular agriculture, Eco-innovation, Environmental management, Green economy transition.

1 | Introduction

The intensification of global agriculture over the past five decades has relied heavily on the use of agrochemicals such as fertilizers, herbicides, insecticides, and fungicides [1–3]. These chemical inputs have

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been instrumental in achieving high crop yields and sustaining food security for a growing population [4–7]. However, their extensive and often indiscriminate application has also generated serious environmental challenges, including soil degradation, water contamination, biodiversity loss, and greenhouse gas emissions [8–10]. As agricultural production systems face increasing scrutiny for their ecological footprint, there is a growing need to reassess the role of agrochemicals in the broader context of environmental sustainability and the transition toward greener economic models [11–14].

In recent years, the discourse surrounding agrochemical use has evolved from one focused purely on productivity and efficiency to one that emphasizes sustainability, resource efficiency, and ecological resilience [11], [14], [15]. This transformation aligns with global sustainability frameworks such as the United Nations Sustainable Development Goals (SDGs), the Paris Agreement, and the European green deal, all of which call for environmentally responsible agricultural practices [17–20].

Concepts such as the green economy, bioeconomy, and circular economy have gained prominence as guiding paradigms for reducing waste, recycling nutrients, and promoting renewable inputs [21–26]. Within this emerging landscape, agrochemical research is increasingly being reframed through a sustainability lens, focusing on the development of eco-innovations that balance agricultural productivity with environmental integrity.

Despite the expanding attention to sustainable agriculture, the scientific literature on agrochemicals remains fragmented across multiple disciplines, including agronomy, environmental science, biotechnology, and economics. Previous studies have examined aspects such as pesticide management, nutrient efficiency, and ecological risk assessment, but few have explored how these strands of research collectively contribute to the transition toward a green and circular economy.

Moreover, while numerous studies have analyzed specific environmental impacts of agrochemicals, there remains limited understanding of how global research collaboration, knowledge networks, and thematic evolution have shaped this field over time. Addressing these gaps is essential for understanding the intellectual structure of sustainability-oriented agricultural research and identifying emerging directions for innovation and policy development.

Recent advances in bibliometric analysis provide valuable tools for mapping large-scale research landscapes and identifying knowledge dynamics across time and space [27–29]. By combining performance indicators, co-authorship, co-citation, and keyword co-occurrence analyses, bibliometrics enables a holistic examination of how scientific knowledge evolves, who the major contributors are, and what emerging themes drive future research [30], [31]. Applying this approach to the study of agrochemicals and sustainability allows for a systematic understanding of how scientific communities have responded to environmental and economic imperatives, and how these responses align with the broader transition toward green growth and circularity in agriculture.

Therefore, this study aims to map and analyze the global research landscape connecting agrochemicals, environmental sustainability, and the green economy. Using bibliometric techniques and data retrieved from the Scopus database covering the period 1976–2025, this study investigates publication trends, author and institutional collaborations, international partnerships, keyword co-occurrence patterns, and reference co-citation networks.

The findings provide a comprehensive overview of the thematic evolution, collaborative structures, and emerging priorities that characterize the intersection between agrochemicals and sustainable economic development. By elucidating these patterns, this research contributes to a deeper understanding of how agricultural science is advancing toward more sustainable and environmentally integrated paradigms.

2 | Methods

This study employed a bibliometric approach to map and analyze the global research landscape connecting agrochemicals, environmental sustainability, and the green economy. All bibliographic data were retrieved

from the Scopus database, which provides extensive multidisciplinary coverage and is widely recognized for bibliometric research. The search was conducted on 17 October 2025 using the following query:

(agrochemical OR "agricultural chemical*" OR pesticide* OR herbicide* OR insecticide* OR fungicide* OR fertilizer* OR "crop protection" OR "chemical input*" OR "farm input*" OR "agricultural management" OR "pest management") AND ("green economy" OR "bioeconomy" OR "circular economy" OR "sustainable economy" OR "green growth" OR "low-carbon economy" OR "sustainable agriculture" OR "sustainable farming" OR "eco-innovation" OR "green technology" OR "clean technology" OR "environmentally friendly" OR "eco-friendly") AND (environment* OR "environmental impact" OR "environmental risk" OR "environmental sustainability" OR "environmental pollution" OR "environmental management" OR "ecological impact" OR "ecological sustainability" OR "ecosystem" OR "pollution" OR "contamination" OR "climate change" OR "soil quality" OR "water quality").*

The initial search across all fields returned 216,325 records. When limited to titles, abstracts, and keywords, the dataset narrowed to 81,235 documents, of which 81,084 were published between 1976 and 2025. After filtering for the English language and excluding non-relevant subject areas using the "AND NOT ALL" operator (e.g., Nanoparticles, Drug effect, Metabolism, Polymer, and other biomedical or materials-science topics), the dataset was reduced to 8,479 documents.

Finally, the dataset was refined to include only peer-reviewed journal articles, resulting in a final sample of 6,189 publications. This multi-stage filtering process ensured that the dataset was both thematically consistent and scientifically relevant to agrochemical and sustainability research. *Fig. 1* illustrates the methodological workflow and document-selection process following the PRISMA-style framework used to visualize metadata acquisition and refinement.

Bibliometric mapping was conducted using VOSviewer (v 1.6.20) for co-authorship (authors, organizations, and countries), co-occurrence (author keywords), and co-citation (references). CiteSpace (v 6.2) was applied to identify keyword citation bursts and to visualize temporal thematic evolution. The Scopus metadata were exported in CSV format and converted into Web of Science-compatible format using CiteSpace's internal converter for accurate burst detection.

Network normalization employed the association-strength method, and occurrence thresholds were applied to ensure interpretability of the visualizations. All clusters were automatically generated by the software and subsequently refined manually for thematic clarity.

The analyses incorporated several performance indicators, including publication counts, citation frequencies, Total Link Strength (TLS), and keyword occurrence. Each analytical dimension provided a distinct layer of insight: performance analysis captured research dynamics, co-authorship mapping revealed collaboration structures, keyword co-occurrence reflected thematic focuses, and co-citation mapping identified the intellectual foundations of the field. Together, these methods enabled a comprehensive and multi-perspective understanding of the evolution of sustainability-oriented agrochemical research.

This study adhered to ethical and methodological standards for bibliometric research. All analyzed data were publicly accessible from a reputable scholarly database, ensuring transparency and reproducibility. No human subjects or confidential materials were involved. The methodological framework aligns with best-practice guidelines for bibliometric studies in agricultural and environmental sciences, ensuring analytical rigor, validity, and replicability of results.

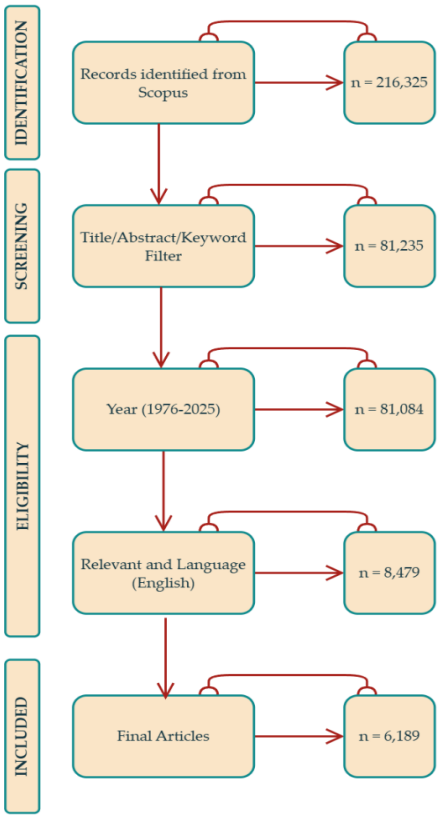

Fig. 1. PRISMA flow diagram of the literature selection process.

3 | Results

3.1 | Trends in Publications and Citations

The bibliometric analysis revealed a consistent rise in scholarly output related to agrochemicals, environmental sustainability, and the green economy during the period 1976–2025. As illustrated in *Fig. 2*, publication activity has accelerated particularly after 2018, reflecting the growing academic focus on sustainable agricultural practices and the ecological implications of chemical inputs. The number of publications peaked in 2023 with 494 articles, followed by 2022 (422 articles) and 2021 (401 articles), while 2020 and 2018 also recorded substantial outputs with 384 and 248 publications, respectively.

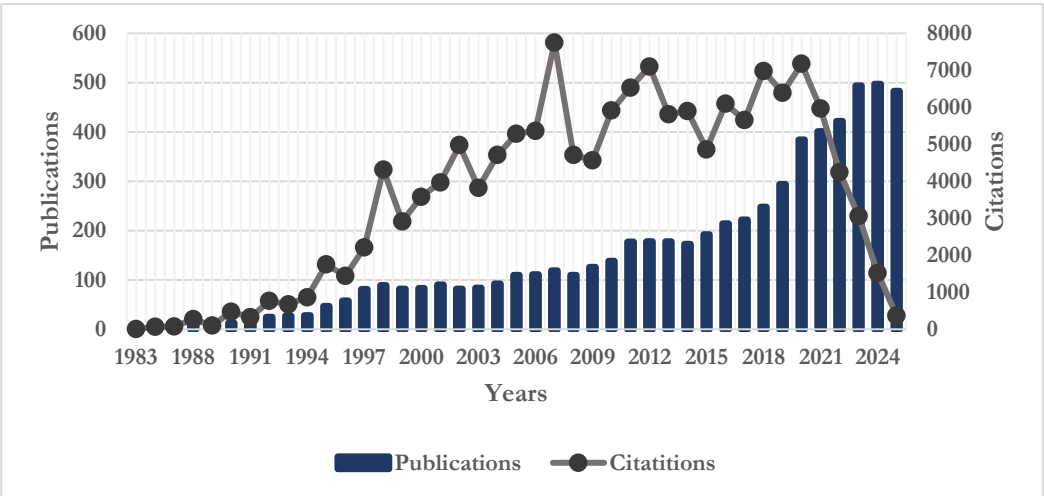

Fig. 2. Trends of publications and citations on agrochemicals, environmental sustainability, and green economy studies.

Although 2023 produced the highest publication volume, 2020 recorded the highest citation count (7,177 citations), indicating that research published during this period had a stronger and more lasting academic influence. The increasing citation impact from 2018 onward aligns with global efforts to promote sustainable agricultural management and policy frameworks addressing the environmental consequences of agrochemical usage.

Table 1 presents the top five years by publications and citations, confirming the overall upward trajectory of research productivity and influence. The normalized scores (N-Pub, N-Cit, and OS) show that 2020 remains the most impactful year overall (OS = 0.849), followed by 2021 (0.788). These findings suggest that the intersection of agrochemicals and green economy discourses has gained substantial traction in the last decade, coinciding with the broader integration of sustainability frameworks in agricultural sciences.

Table 1. Top five years by publications and citations on agrochemicals, environmental sustainability, and green economy studies.

Year	Pub.	Cit.	N-Pub	N-Cit	OS
2020	384	7177	0.772	0.926	0.849
2021	401	5970	0.806	0.770	0.788
2018	248	6984	0.498	0.901	0.700
2022	422	4247	0.849	0.548	0.698
2023	494	3062	0.994	0.395	0.695

Note: Pub = publications; Cit = citations; N-Pub/Cit = normalized values (max = 1.000); OS = Overall score (composite index).

3.2 | Author Collaboration Network

The co-authorship network *Fig. 3* comprises 513 authors organized into 23 clusters, connected by 2,893 links with a TLS of 3,731. This structure indicates a well-developed but moderately dense collaborative landscape, where several active researchers maintain interconnected research agendas on sustainable agrochemical use and environmental management.

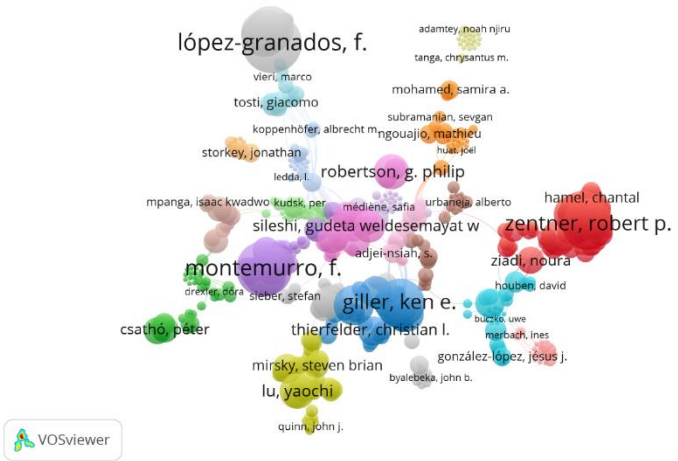

Fig. 3. Authors co-authorship network on agrochemicals, environmental sustainability, and green economy studies (Items: 513, Clusters: 23, Links: 2893, TLS: 3731).

As summarized in *Table 2*, López-Granados, F. emerges as the most prolific author, contributing 22 publications with 1,465 citations and a strong TLS value of 72 (OS = 0.858). Other notable contributors include Zentner, R.P., Campbell, C.A., Giller, K.E., and Montemurro, F., all of whom have consistently advanced research in areas such as crop protection, fertilizer efficiency, and integrated pest management. The co-authorship clusters reveal that collaborations tend to form around shared thematic interests rather than geographic proximity, suggesting that the field's evolution has been driven by topical specialization and cross-institutional cooperation.

Table 2. Leading authors by publications, citations, and TLS.

Author	Pub.	Cit.	TLS	N-Pub	N-Cit	N-TLS	OS	Cluster
López-Granados, F.	22	1465	72	1.000	0.823	0.750	0.858	20
Zentner, Robert P.	18	1189	96	0.810	0.668	1.000	0.826	1
Campbell, Constantine A.	17	1185	81	0.762	0.666	0.844	0.757	1
Giller, Ken E.	17	1780	28	0.762	1.000	0.292	0.685	3
Montemurro, F.	20	428	67	0.905	0.240	0.698	0.614	5

Note: Pub = publications; Cit = citations; TLS = total link strength N-Doc/Cit/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

3.3 | Organizations Collaboration Network

The organizational collaboration network *Fig. 4* consists of 867 institutions divided into 34 clusters, linked through 3,922 connections with a cumulative TLS of 4,357. These metrics demonstrate that institutional cooperation in agrochemical and sustainability research has expanded globally, although the network still exhibits regional clustering.

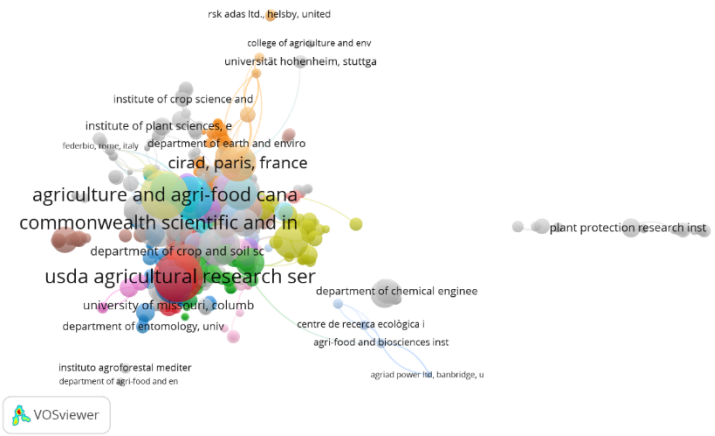
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Fig. 4. Organizations co-authorship network on agrochemicals, environmental sustainability, and green economy studies (items: 867, clusters: 34, links: 3922, TLS: 4357).

According to *Table 3*, the U.S. Department of Agriculture (USDA) agricultural research service ranks first in both publication count (68) and citation impact (3,284), with the highest composite score (OS = 0.943). Agriculture and Agri-Food Canada follows closely (OS = 0.807), while European research institutions such as INRAE (France) and CSIRO (Australia) also play central roles in international collaboration.The presence of CIRAD (France) further highlights the importance of research cooperation between developed and developing regions, especially in sustainable pest management and soil fertility improvement.

Despite the diversity of contributing institutions, the network still shows moderate fragmentation, with strong intraregional clusters in North America and Europe but weaker linkages with institutions in Asia, Africa, and Latin America. This imbalance suggests a need for greater South-North collaboration to bridge research capacities and address localized environmental challenges related to agrochemical management.

Table 3. Top contributing organizations by publications, citations, and collaboration strength.

Organization	Pub.	Cit.	TLS.	N-Pub	N-Cit	N-TLS	OS	Cluster
The USDA agricultural research service	68	3284	68	1.000	1.000	0.829	0.943	1
Agriculture and agri-food Canada	65	2728	52	0.955	0.831	0.634	0.807	13
French national research institute for agriculture, food and environment	47	2047	82	0.687	0.623	1.000	0.770	29

Table 3. Continued.

Organization	Pub.	Cit.	TLS.	N-Pub	N-Cit	N-TLS	OS	Cluster
The commonwealth scientific and industrial research organisation	65	2922	27	0.955	0.890	0.329	0.725	24
Center cooperation international in agricultural research development	38	1347	81	0.552	0.410	0.988	0.650	16

Note: Pub = publications; Cit = citations; TLS = total link strength N-Doc/Cit/TLS = normalized values (max = 1.000); OS = Overall score (composite index).

3.4 | International Collaboration by Country

The international co-authorship analysis (*Fig. 5*) reveals that 153 countries contribute to the literature on agrochemicals and sustainable economy, organized into 17 clusters, forming 1,113 links with a TLS of 3,222. The United States clearly dominates this research field, producing 1,247 publications with 39,748 citations and the highest collaboration intensity (TLS = 465; OS = 1.000). This reflects the United States' longstanding leadership in agricultural innovation and environmental policy research.

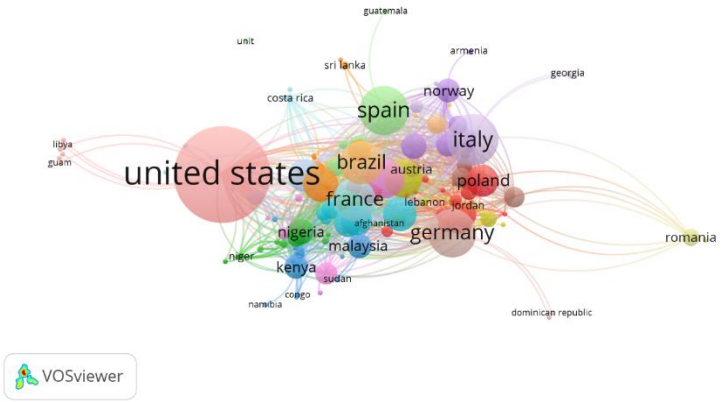

Fig. 5. International co-authorship network of countries on agrochemicals, environmental sustainability, and green economy studies (items: 153, Clusters: 17, Links: 1113, TLS: 3222).

As shown in *Table 4*, other major contributors include Germany, Italy, Spain, and France, each maintaining high publication and citation counts with strong inter-European collaborations. European countries are characterized by a high degree of thematic cohesion around sustainable agriculture and circular economy applications, while North American research tends to emphasize technological efficiency and agrochemical management systems.

The comparatively lower TLSs outside Europe and North America indicate that international collaboration remains concentrated among developed economies. Strengthening cooperative research between developed and developing nations could enhance the global diffusion of sustainable agricultural technologies and practices.

Table 4. Top countries by publications, citations, and TLS.

Country	Pub.	Cit.	TLS	N-Pub	N-Cit	N-TLS	OS	Cluster
United States	1247	39748	465	1.000	1.000	1.000	1.000	10
Germany	370	12192	390	0.296	0.307	0.839	0.481	17
Italy	414	12516	348	0.331	0.315	0.748	0.465	14
Spain	387	13438	310	0.310	0.338	0.667	0.438	11
France	302	10002	367	0.242	0.252	0.789	0.427	15

Note: Pub = publications; Cit = citations; TLS = total link strength N-Doc/Cit/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

3.5 | Author Keyword Co-Occurrence Analysis

Keyword co-occurrence mapping (*Fig. 6*) generated 1,000 items grouped into 17 clusters, connected by 12,627 links with a TLS of 15,597. This dense network underscores the multidimensional nature of research combining agrochemicals, sustainability, and the green economy.

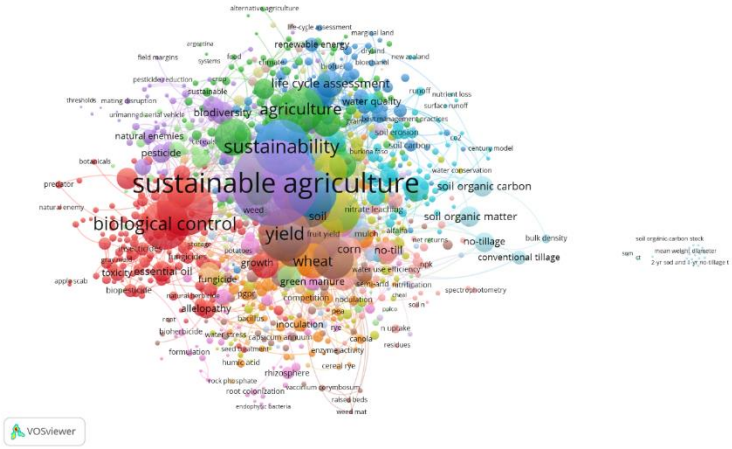

Fig. 6. Author keyword co-occurrence on agrochemicals, environmental sustainability, and green economy studies (items: 1000, clusters: 17, links: 12627, TLS: 15597).

As presented in *Table 5*, the most frequent keywords include "sustainable agriculture" (290 occurrences), "sustainability" (154), "integrated pest management" (157), and "fertilizer" (126), reflecting the field's increasing attention to environmentally responsible input management.

Other prominent terms such as "yield," "nitrogen," and "biological control" highlight the dual emphasis on productivity and ecological balance.

The results suggest a strong convergence between agronomic efficiency and sustainability objectives, where scholars seek to optimize chemical input use while mitigating environmental degradation. The prominence of "compost," "maize," and "biological control" further indicates the shift toward organic amendments and biocontrol strategies as key alternatives to conventional agrochemicals.

Table 5. Top 10 author keywords.

Author Keyword	Occ.	TLS	N-Occ	N-TLS	OS	Cluster
Sustainable agriculture	290	659	1.000	1.000	1.000	5
Sustainability	154	327	0.529	0.494	0.512	3
Yield	140	358	0.481	0.541	0.511	8
Integrated pest management	157	319	0.540	0.482	0.511	1
Nitrogen	122	389	0.419	0.588	0.504	8
Fertilizer	126	315	0.433	0.476	0.454	3
Biological control	130	262	0.446	0.395	0.421	1
Agriculture	117	279	0.401	0.421	0.411	2
Compost	99	292	0.339	0.441	0.390	8
Maize	105	269	0.360	0.405	0.383	4

Note: Occ = occurrence; TLS = total link strength N-Occ/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

Table 6. Top 10 author keywords with the strongest citation bursts.

Keywords	Year	Strength	Begin	End	1995-2025
Sustainable agriculture	1995	33.54	1995	2001	
Soil organic matter	2006	23.06	2008	2017	
Sustainable development	2006	15.98	2018	2025	
Climate change	2013	20.64	2020	2025	
Agricultural robots	2015	19.58	2020	2021	
Nutrients	2017	25.57	2017	2023	
Forestry	2017	16.27	2017	2021	
Anaerobic digestion	2018	26.71	2019	2025	
Biogas	2019	16.29	2019	2023	
Circular economy	2021	32.02	2021	2025	

The keyword burst analysis (*Table 6*) provides temporal insights into emerging topics. Early bursts such as "sustainable agriculture" (1995–2001) and "soil organic matter" (2008–2017) represent foundational research themes. More recent bursts "climate change" (2020–2025), "anaerobic digestion" (2019–2025), and "circular economy" (2021–2025) reveal the field's transition toward systems-level sustainability and waste valorization. The rise of "biogas" and "nutrients" as strong citation bursts also indicates the growing intersection between agricultural chemistry and renewable energy research. Overall, the burst trends reflect an evolution from traditional input-based agronomy to holistic environmental management frameworks that align with circular and low-carbon economic paradigms.

3.6 | Reference Co-Citation Analysis

The reference co-citation network *Fig. 7* includes 974 cited sources distributed across 28 clusters, connected by 4,312 links with a TLS of 5,259, demonstrating a well-established but diverse intellectual base.

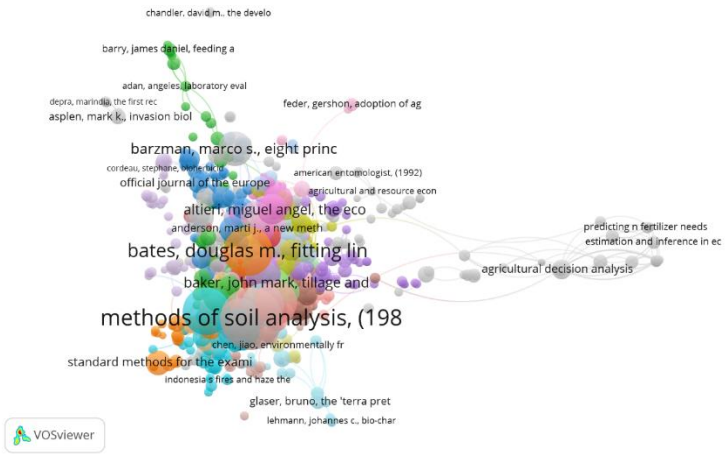
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Fig. 7. Reference co-citation network on agrochemicals, environmental sustainability, and green economy studies (items: 974, clusters: 28, links: 4312, TLS: 5259).

Table 7 lists the most frequently co-cited works, led by Anderson and Ingram [32] on methods of soil analysis with 75 citations, followed by Bates [32] on linear mixed-effects models (lme4) and Bray (1945) on phosphorus determination methods. These seminal references underline the methodological and analytical foundations underpinning soil and agrochemical research.

The inclusion of Anderson and Ingram [32] further reinforces the field's reliance on methodological rigor in soil characterization and fertility evaluation. The co-citation clusters indicate two dominant intellectual streams: 1) empirical agronomic research focused on nutrient dynamics and soil health, and 2) methodological frameworks emphasizing data modeling and environmental quantification.

Table 7. Top five most co-cited reference.

Author	Title	Year	Citations	Cluster
Anderson, John P.E.	Methods of soil analysis	1982	75	17
Bates, Douglas M.	Fitting linear mixed-effects models using lme4	2015	53	7
Bray, Roger H.	Determination of total, organic, and available forms of phosphorus in soils	1945	50	6
Blake, George R.	Bulk density	2018	42	10
Anderson, J.M. & Ingram, J.S.I.	Tropical soil biology and fertility: a handbook of methods	1993	42	6

Together, these streams shape the scientific foundation of contemporary agrochemical sustainability research. The frequent co-citation of methodological papers suggests that bibliometric patterns in this domain are strongly shaped by the integration of advanced analytical tools with applied environmental and agricultural studies.

4 | Discussion

The results of this study demonstrate a continuous expansion of research at the intersection of agrochemicals, environmental sustainability, and the green economy from 1976 to 2025. The upward trend in publications and citations reflects the increasing global recognition of the environmental challenges associated with agrochemical use and the growing interest in sustainable agricultural practices [33–36]. The significant increase in scientific output after 2018 corresponds with global policy initiatives emphasizing low-carbon and resource-efficient agricultural systems. This trend highlights the shift from traditional productivity-driven studies toward sustainability-oriented research that integrates ecological, technological, and economic considerations. The rise in citation counts around 2020 also indicates a maturing body of work, as studies from that period began influencing environmental management and policy discourses more directly.

The authorship collaboration network illustrates how research on agrochemicals and sustainability has evolved into a multidisciplinary and increasingly interconnected field. Leading researchers such as López-Granados, Zentner, Campbell, Giller, and Montemurro represent clusters that bridge agronomy, environmental science, and technological innovation. Their high citation impact and TLS suggest strong intellectual leadership and the presence of collaborative teams that transcend disciplinary boundaries. The gradual densification of the author network signifies an important structural transition, moving from isolated studies toward globally coordinated research communities. This development mirrors a broader trend in environmental and agricultural sciences, where complex sustainability challenges demand collaborative and integrative approaches [37–40].

The institutional collaboration patterns further emphasize the role of research organizations as central hubs of knowledge production. Institutions such as the USDA Agricultural Research Service, Agriculture and Agri-Food Canada, and INRAE in France emerge as the main nodes linking global networks of agricultural and environmental research. Their extensive collaborations and high citation performance demonstrate the strong institutional support and research infrastructure available in developed countries. Meanwhile, emerging organizations in the Global South, including the Africa Rice Center and CGIAR-affiliated institutions, indicate increasing engagement from developing regions.

However, their relatively low TLS and citation rates reflect disparities in research capacity, funding, and access to international collaboration. Strengthening institutional networks in underrepresented regions remains essential to building more balanced and inclusive global research ecosystems [34], [35].

The country-level collaboration analysis supports these institutional findings. The dominance of the United States, Germany, Italy, Spain, and France demonstrates how research capacity and funding directly influence global leadership in the agrochemical sustainability domain. European countries, in particular, show strong internal linkages and thematic coherence driven by continental initiatives such as the European Green Deal and the Bioeconomy Strategy [43–45].

In contrast, developing countries often participate as secondary collaborators, with limited representation as primary research leaders. The participation of nations such as Ghana, Morocco, and Ethiopia signals an emerging shift, but collaboration remains asymmetrical. This disparity underscores the need for targeted capacity-building programs, South–South cooperation, and policy alignment to strengthen the participation of tropical and developing nations in sustainability-focused agricultural research [46].

The keyword co-occurrence and burst analyses reveal the intellectual trajectory of the field. Earlier studies focused on traditional agrochemical management topics such as pesticides, fertilizers, and weed control [47–50]. Over time, the discourse has expanded toward concepts like sustainable agriculture, biochar, biogas, anaerobic digestion, and the circular economy [52–54].

These developments reflect a growing alignment between agricultural chemistry and environmental stewardship [54–56]. The increasing prominence of terms such as climate change, renewable energy, and nutrient recycling suggests that contemporary agrochemical research is evolving toward closed-loop systems that minimize waste and emissions [58–62]. The transition from linear input-output models to circular agricultural frameworks indicates a broader epistemological shift in how sustainability is conceptualized and operationalized within the agrochemical context [53], [54].

The reference co-citation network provides further insight into the intellectual foundations of this transition. Classical agronomic references, including Anderson's Methods of Soil Analysis and Bray's early work on phosphorus quantification, remain central, demonstrating the enduring importance of methodological rigor. However, more recent works such as the Farm to Fork Strategy, the Billion Ton Report, and A Sustainable Bioeconomy for Europe reveal the growing influence of policy and systemic perspectives on sustainability research.

This convergence of empirical and policy-oriented studies suggests that the field is moving toward an integrated analytical framework, combining experimental evidence with broader environmental and socio-economic modeling. The frequent co-citation of methodological papers and policy reports demonstrates how scientific knowledge is increasingly being mobilized to inform sustainability transitions at multiple scales.

Collectively, these findings portray a field in transformation. The research on agrochemicals and sustainable economy has moved beyond measuring environmental impacts toward designing solutions that harmonize productivity, ecology, and economic resilience [64]. The growing diversity of authors, institutions, and keywords reflects the multidimensionality of the topic, encompassing agronomic efficiency, climate adaptation, and green innovation.

However, the analysis also highlights persistent structural imbalances. Developed countries continue to dominate publication output, research funding, and policy influence, while developing regions remain underrepresented despite facing the most severe environmental risks from agrochemical use. Addressing these inequalities requires international collaboration frameworks that emphasize equitable participation, knowledge exchange, and locally adapted innovation.

While this study provides a comprehensive bibliometric overview of agrochemical and sustainability research, it also faces several limitations. The reliance on Scopus as the sole data source may exclude relevant publications indexed in other databases such as Web of Science or regional repositories. Language bias may also result in the underrepresentation of non-English literature, particularly from Asia and Latin America.

Furthermore, the bibliometric approach emphasizes quantitative relationships and may overlook qualitative nuances such as contextual drivers, policy diversity, and socio-cultural dimensions of sustainability. Future research could address these limitations by combining bibliometric analysis with content-based or text-mining approaches to capture the evolving narratives and value systems within this field. Expanding collaboration with regional experts and incorporating local case studies would also strengthen the relevance and inclusiveness of future assessments.

5 | Conclusion

This study mapped and analyzed global research on agrochemicals in relation to environmental sustainability and the green economy from 1976 to 2025. The results reveal a clear thematic transition from productivity-oriented studies to sustainability-centered research integrating concepts such as biochar, nutrient recycling,

and circular agriculture. Collaboration networks indicate that Europe and North America dominate scientific production and influence, while participation from developing countries is gradually increasing. These findings confirm a progressive shift toward an integrated understanding of agrochemical use within sustainable and low-carbon agricultural systems.

The study contributes to the literature by providing a comprehensive overview of how scientific knowledge on agrochemicals has evolved in response to environmental and economic imperatives. It highlights the growing alignment between agricultural management, environmental policy, and technological innovation, emphasizing the importance of collaborative and interdisciplinary approaches to achieve sustainable agricultural transitions. The bibliometric insights presented here can inform both research agendas and policy frameworks aiming to reduce chemical dependency and promote resource-efficient farming practices.

Although limited to publications indexed in Scopus, this analysis offers a robust foundation for future research on sustainable agrochemical management. Subsequent studies could integrate multiple databases, apply qualitative or text-mining techniques, and include local or regional case studies to capture diverse sustainability pathways. Strengthening collaborations between developed and developing regions will be essential to ensure that the global transition toward sustainable agriculture is inclusive, equitable, and scientifically informed.

Author Contributaion

"Conceptualization, Qalbin Salim Fazli and Ghazi Mauer Idroes.; Methodology, Qalbin Salim Fazli.; Software, Qalbin Salim Fazli; Validation, Ghazi Mauer Idroes., Iin Shabrina Hilal., Daniel Balsalobre-Lorente., Putri Maulidar; Formal analysis, Ghazi Mauer Idroes and Daniel Balsalobre-Lorente.; Investigation, Putri Maulidar and Iin Shabrina Hilal.; writing-reviewing and editing, Qalbin Salim Fazli.

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Data Availability

Data will be made available on request.

Conflicts of Interest

The authors declare no conflict of interest.

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